A compilation of metallic systems that show a quantum ferromagnetic transition

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We provide a compilation of metallic systems in which a low-temperature ferromagnetic or similar transition is observed. Our objective is to demonstrate the universal first-order nature of such transitions in clean systems in two or three spatial dimensions. Please contact the authors with information about omissions, corrections, or any other information.

Quantum phase transitions are phenomena of great interest.[1,2] Perhaps the most obvious quantum phase transition, and the first one considered historically, is the transition from a paramagnetic metal to a ferromagnetic metal at zero temperature ($T = 0$) as a function of some non-thermal control parameter. Stoner's theory of itinerant ferromagnetism[3] describes both the thermal transition and the static properties of the quantum transition in a mean-field approximation. It predicts a second-order or continuous transition with standard Landau or mean-field static critical exponents. For the thermal or classical transition this constitutes an approximation for spatial dimensions $d \leq 4$. In the physical dimensions $d = 3$ or lower, fluctuations of the magnetization order parameter, which are neglected in Stoner theory, lead to deviations from the mean-field critical behavior that require the renormalization group (RG) for a theoretical understanding.[4] In a seminal paper, Hertz[1] derived a Landau-Ginzburg-Wilson (LGW) functional for the ferromagnetic transition from a model of itinerant electrons that interact via a point-like potential in the particle-hole spin-triplet channel. Hertz analyzed this dynamical LGW functional by means of RG methods. He concluded that, at $T = 0$, Stoner theory is exact as far as the static critical behavior is concerned, i.e., the transition is of second order with mean-field static critical exponents, and a dynamical critical exponent $z = 3$, for all $d > 1$. This is because the coupling of the statics to the dynamics makes the system effectively behave as if it were in a higher spatial dimension, given by $D = d + z$.

It became clear in the late 1990s that this theoretical picture is not correct. It was shown that particle-hole excitations about the Fermi surface, which exists in all metals in dimensions $d > 1$, couple to the magnetization and invalidate Hertz's conclusions.[5,14] As a result, the quantum ferromagnetic transition was predicted to be generically of first order in clean metallic ferromagnets in $d > 1$. Physically, the mechanism that drives the transition first order is very similar to the fluctuation-induced first-order transition that was predicted earlier for the classical transition in superconductors and smectic liquid crystals,[6] and to the spontaneous mass-generation mechanism known as the Coleman-Weinberg mechanism in particle physics.[7] In all of these cases a generic soft mode (the photon in the cases of superconductors and scalar electrodynamics; the nematic Goldstone mode in the case of liquid crystals) that is distinct from the order parameter fluctuations couples to the latter and qualitatively changes the nature of the phase transition. For the quantum ferromagnetic transition in metals, the resulting prediction is the generic phase diagram shown in Fig. 1. At zero temperature ($T = 0$), there is a first-order transition triggered by a non-thermal control parameter t. A nonzero temperature gives the generic particle-hole excitations a mass, and as a result the mechanism driving the first-order transition becomes weaker with increasing

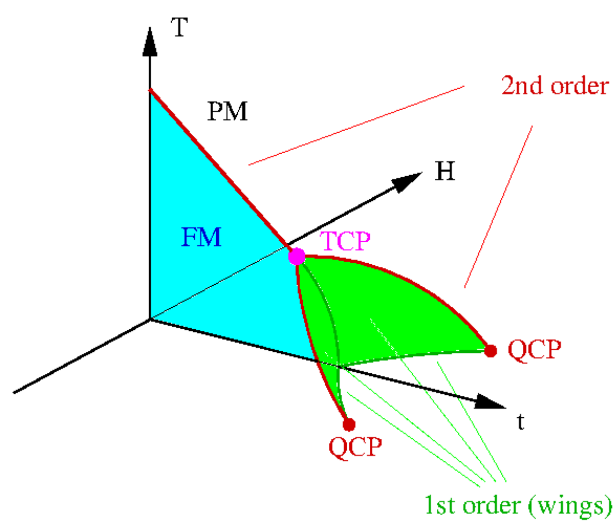

FIG. 1: Generic phase diagram of a metallic ferromagnet in the space spanned by temperature (T), magnetic field (H), and the control parameter (t). Shown are the ferromagnetic (FM) and paramagnetic (PM) phases, lines of second-order transitions, surfaces of first-order transitions ("tricritical wings"), the tricritical point (TCP), and the two quantum critical points (QCP).

temperature. This leads to a tricritical point (TCP) at some temperature $T_{\rm tc} > 0$, and for $T > T_{\rm tc}$ the transition is generally of second order with classical critical exponents. Upon the application of an external field conjugate to the order parameter, i.e., a homogeneous magnetic field H in the case of a ferromagnet, surfaces of first-order transitions called tricritical wings emerge from the tricritical point. This is true for any classical phase diagram that contains a tricritical point,[8] and it holds for quantum ferromagnets as well.[9] These tricritical wings are bounded by lines of second-order transitions and end in a pair of quantum critical points (QCPs) in the $T = 0$ plane. The critical behavior at these QCPs can be determined exactly and is a slight modification of the critical behavior predicted by Hertz for the quantum phase transition at $H = 0$ that is pre-empted by the first-order transition.[9]

This general picture is theoretically predicted to apply to all transitions from a metallic paramagnetic phase to a metallic ferromagnetic one in dimensions $d > 1$, irrespective of whether the magnetism is caused by the conduction electrons ("itinerant ferromagnets") of by electrons in a different band, and irrespective of the isotropy or lack thereof of the magnetization. That is, it applies to easy-axis (Ising) and easy-plane (XY) magnets as well as to isotropic (Heisenberg) magnets. It also applies to ferrimagnets and canted ferromagnets, and more generally to any metallic system that has a nonvanishing homogeneous magnetization,[10] but the most extensive experimental information is available for ferromagnets. There are only two ways to avoid these conclusions: (1) In 1-d or quasi-1-d systems there is no Fermi surface, and hence no particle-hole excitations, and the soft-mode mechanism is not operative. (2) In the presence of sufficiently strong quenched disorder the nature of the particle-hole excitations changes from ballistic to diffusive, and the nature of the coupling to the magnetization changes as well. This can lead to a second-order quantum phase transition with non-mean-field critical exponents that still can be determined exactly.[11–14] Disorder may also have stronger effects, leading to Griffiths phases and smeared transitions, see Ref. 15.

Experimentally, the picture summarized above is confirmed with remarkable uniformity. To the authors's knowledge, all metallic ferromagnets that do not fall into one of the two exceptional classes mentioned above, show a first-order transition if the transition temperature is sufficiently low, or can be driven sufficiently low by a nonthermal control parameter, such as pressure, or composition. This is especially remarkable if compared with the case of classical liquid crystals, where the observed transition is usually of second order, and only recently have examples of weakly first-order transitions been found.[16] The reason why the theory is so much more successful in the quantum case is not entirely understood, but it is likely related to the fact that order-parameter fluctuations, which can invalidate the fluctuation-induced first-order mechanism, are strongly suppressed in the quantum case for the same reasons that lead to a mean-field critical behavior in Hertz's theory.[10]

The purpose of this informal communication is to demonstrate this remarkable agreement between theory and experiment by compiling a list of metallic systems in which a quantum ferromagnetic transition has been observed. The systems are listed roughly in order of completeness of the experimental information available. All but three of the systems listed display a confirmed or suspected first-order transition. The three expections are, $\rm URu_{2-x}Re_xSi_2$, which is strongly disordered, $\rm YbNi_4P_2$, which is quasi-1-d, and $\rm Ni_xPd_{1-x}$, where the lowest transition temperature achieved is 7K, which may be above the tricritical point, if one exists. All other examples are consistent with the phase diagram shown in Fig. 1. In some cases (e.g., UCoGe) the transition is first order at the highest, or only, temperature observed, so the tricritical point is not accessible. In all cases where a tricritical point is accessible and the behavior in a magnetic field has been studied, tricritical wings have been observed. One of the best studied materials, MnSi, is actually a helimagnet,[17] but the helical wavelength ($\approx 200\mathring{A}$) is so long compared to the atomic length scale that the system is well approximated as a ferromagnet.[18]

We conclude with a few general remarks. First, there also are cases of transitions from a metallic ferromagnet to some insulating phase. Examples include, $\rm FeSi_{1-x}Ge_x$,[19] and $\rm RE_{0.55}Sr_{0.45}Mn_3$, with RE a rare earth or a combination of rare earths.[20] In these cases the theoretical situation is more complicated, and we do not include them in our discussion. Second, in any given material a first-order transition may occur for reasons other than the coupling to particle-hole excitations. This is likely the case in systems that have a tricritical point at a relatively high temperature, such as various manganites, see, e.g., Ref. 21. Finally, we mention that some of the materials listed in the table have gotten a lot of attention for properties other than, although possibly related to, the ferromagnetic transition. Examples are the coexistence of superconductivity and ferromagnetism observed in $\rm UGe_2$,[22] URhGe,[23] and UCoGe,[24] or the non-Fermi-liquid phase and the A-phase in MnSi.[25,26] As a result, there is a large body of literature on some of these materials; we quote only papers that are directly relevant to properties reflected by the entries in the table.

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TABLE I: Systems with low-T ferromagnetic transitions and their properties. T_c = Curie temperature, T_{tc} = tricritical temperature. ρ_0 = residual resistivity. FM = ferromagnet, SC = superconductor. N/A = not applicable; n.a. = not available.

System [a]	Order of Transition[c]	T_c/K [b]	magnetic moment/μ_B [d]	tuning parameter	T_{tc}/K	wings observed	Disorder ($\rho_0/\mu\Omega$cm)[e]	Comments
MnSi [27]	1st [18]	29.5 [28]	0.4 [28]	hydrostatic pressure [18]	≈ 10 [18]	yes [25]	0.33 [25]	weak helimagnet [17] exotic phases [25,26]
$ZrZn_2$ [27]	1st [29]	28.5 [29]	0.17 [29]	hydrostatic pressure [29]	≈ 5 [29]	yes [29]	≥ 0.31 [30]	confusing history, see Ref. 27
$Sr_3Ru_2O_7$	1st [f]	0 [g]	0 [g]	pressure [g]	n.a.	yes [31]	< 0.5 [31]	foliated wing tips, nematic phase [31]
UGe_2 [33]	1st [34]	52 [35]	1.5 [35]	hydrostatic pressure [22,35]	24 [36]	yes [35,36]	0.2 [22]	easy-axis FM coexisting FM+SC [22]
URhGe [33]	1st [37]	9.5 [23]	0.42 [23]	transverse B-field [37,39]	≈ 1 [37]	yes [37]	8 [38]	easy-plane FM coexisting FM+SC [23]
UCoGe [33]	1st [40]	2.5 [40]	0.03 [24]	none	> 2.5? [h]	no	12 [24]	coexisting FM+SC [24]
CoS_2	1st [41]	122 [41]	0.84 [41]	hydrostatic pressure [41]	≈ 120 [41]	no	0.7 [41]	rather high T_c
$La_{1-x}Ce_xIn_2$	1st [42]	22 – 19.5 [42] [i]	n.a.	composition [42]	> 22? [j]	no	n.a.	third phase between FM and PM? [42]
Ni_3Al [27]	(1st) [k]	41 – 15 [l]	0.075 [m]	hydrostatic pressure [43]	n.a.	no	0.84 [44]	order of transition uncertain
$YbIr_2Si_2$ [n]	1st [45]	1.3 – 2.3 [o]	n.a.	hydrostatic pressure [45]	n.a.	no	≈ 22 [p]	FM nature of ordered phase suspected [45]
$YbCu_2Si_2$ [n]	n.a.	4 – 6 [46] [q]	n.a.	hydrostatic pressure [46]	n.a.	no	n.a.	nature of magnetic order unclear
$URu_{2-x}Re_xSi_2$	2nd [47,48]	25 – 2 [r]	0.4 – 0.03 [48]	composition [47]	N/A	N/A	≈ 100 [s]	strongly disordered
Ni_xPd_{1-x}	2nd [50]	600 – 7 [t]	n.a.	composition [50]	N/A	N/A	n.a.	disordered, lowest T_c rather high
$YbNi_4P_2$	2nd [51]	0.17 [51]	≈ 0.05 [51]	none	N/A	N/A	2.6 [51]	quasi-1d, disordered

[a]References in this column refer to reviews, if any exist. Most references are to be understood as "This reference and references therein".
[b]A single value of T_c, for the default value of the tuning parameter (ambient pressure, zero field) is given where a tricritical temperature has also been measured. A range of T_c, with a corresponding range of the control parameter, is given in all other cases.
[c]At the lowest temperature achieved.
[d]Per formula unit unless otherwise noted.
[e]For the highest-quality samples.
[f]Phase diagram not mapped out completely; the most detailed measurements show the tips of the wings. See Ref. 31.
[g]Paramagetic at ambient pressure. Hydrostatic pressure drives the system away from FM, uniaxial stress drives it towards FM. See Ref. 31 and references therein, especially Ref. 32.
[h]1st order transition with no tuning parameter; TCP not accessible.
[i]For $x = 1.0 - 0.9$
[j]1st order for $x = 1$, TCP not accessible.
[k]Suspected 1st order transition near $p = 80$kbar, Refs. 27,43.
[l]For pressures $p = 0 - 60$ kbar, Ref. 43.
[m]Per Ni at $p = 0$, Ref. 43
[n]$YbRh_2Si_2$ belongs to the same family, but has an AFM phase between the FM and the PM.[45].
[o]For pressures $p \approx 8 - 10$GPa.
[p]For a magnetic sample at pressures $p \approx 8 - 10$GPa. Samples with ρ_0 as low as $0.3\mu\Omega$cm have been prepared.[45]
[q]For pressures $p \approx 10 - 20$GPa.
[r]for $x = 0.6 - 0.2$, Ref. 48.
[s]For $x = 0.1$, Ref. 49.
[t]for $x = 1 - 0.027$, Ref. 50

[1] J. Hertz, Phys. Rev. B **14**, 1165 (1976).
[2] S. Sachdev, *Quantum Phase Transitions* (Cambridge University Press, Cambridge, 1999).
[3] E. C. Stoner, Proc. Roy. Soc. London A **165**, 372 (1938).
[4] K. G. Wilson and J. Kogut, Phys. Rep. **12**, 75 (1974).
[5] D. Belitz, T. R. Kirkpatrick, and T. Vojta, Phys. Rev. Lett. **82**, 4707 (1999).
[6] B. I. Halperin, T. C. Lubensky, and S.-K. Ma, Phys. Rev. Lett. **32**, 292 (1974).
[7] S. Coleman and E. Weinberg, Phys. Rev. D **7**, 1888 (1973).
[8] R. B. Griffiths, Phys. Rev. Lett. **24**, 715 (1970).
[9] D. Belitz, T. R. Kirkpatrick, and J. Rollbühler, Phys. Rev. Lett. **94**, 247205 (2005).
[10] T. R. Kirkpatrick and D. Belitz (2012), arXiv:1203.3826.
[11] T. R. Kirkpatrick and D. Belitz, Phys. Rev. B **53**, 14364 (1996).
[12] D. Belitz, T. R. Kirkpatrick, M. T. Mercaldo, and S. Sessions, Phys. Rev. B **63**, 174427 (2001).
[13] D. Belitz, T. R. Kirkpatrick, M. T. Mercaldo, and S. Sessions, Phys. Rev. B **63**, 174428 (2001).
[14] D. Belitz, T. R. Kirkpatrick, and T. Vojta, Rev. Mod. Phys. **77**, 579 (2005).
[15] T. Vojta, J. Low Temp. Phys. **161**, 299 (2010).
[16] A. Yethiraj, R. Mukhopadhyay, and J. Bechhoefer, Phys. Rev. E **65**, 021702 (2002).
[17] Y. Ishikawa, K. Tajima, D. Bloch, and M. Roth, Solid State Commun. **19**, 525 (1976).
[18] C. Pfleiderer, G. J. McMullan, S. R. Julian, and G. G. Lonzarich, Phys. Rev. B **55**, 8330 (1997).
[19] S. Yeo, S. Nakatsuji, A. D. Bianchi, P. Schlottmann, Z. Fisk, L. Balicas, P. A. Stampe, and R. J. Kennedy, Phys. Rev. Lett. **91**, 046401 (2003).
[20] L. Demkò, I. Kézsmárki, G. Mihály, N. Takeshita, Y. Tomioka, and Y. Tokura, Phys. Rev. Lett. **101**, 037206 (2008).
[21] D. Kim, B. Revaz, B. L. Zink, F. Hellman, J. J. Rhyne, and J. F. Mitchell, Phys. Rev. Lett. **89**, 227202 (2002).
[22] S. S. Saxena, P. Agarwal, K. Ahilan, F. M. Grosche, R. K. W. Haselwimmer, M. J. Steiner, E. Pugh, I. R. Walker, S. R. Julian, P. Monthoux, et al., Nature (London) **406**, 587 (2000).
[23] D. Aoki, A. Huxley, E. Ressouche, D. Braithwaite, J. Floquet, J.-P. Brison, E. Lhotel, and C. Paulsen, Nature (London) **413**, 613 (2001).
[24] N. T. Huy, A. Gasparini, D. E. de Nijs, Y. Huang, J. C. P. Klaasse, T. Gortenmulder, A. de Visser, A. Hamann, T. Görlach, and H. v. Löhneysen, Phys. Rev. Lett. **99**, 067006 (2007).
[25] C. Pfleiderer, S. R. Julian, and G. G. Lonzarich, Nature (London) **414**, 427 (2001).
[26] S. Mühlbauer, B. Binz, F. Jonietz, C. Pfleiderer, A. Rosch, A. Neubauer, R. Georgii, and P. Böni, Science **323**, 915 (2009).
[27] C. Pfleiderer, J. Low Temp. Phys. **147**, 231 (2007).
[28] Y. Ishikawa, Y. Noda, Y. J. Uemura, C. F. Majkrzak, and G. Shirane, Phys. Rev. B **31**, 5884 (1985).
[29] M. Uhlarz, C. Pfleiderer, and S. M. Hayden, Phys. Rev. Lett. **93**, 256404 (2004).
[30] M. Sutherland, R. P. Smith, N. Marcano, Y. Zhou, S. E. Rowley, F. M. Grosche, N. Kimura, S. M. Hayden, S. Takashima, M. Nohara, et al., Phys. Rev. B **85**, 035118 (2012).
[31] W. Wu, A. McCollam, S. A. Grigera, R. S. Perry, A. P. Mackenzie, and S. R. Julian, Phys. Rev. B **83**, 045106 (2011).
[32] S.-I. Ikeda, Y. Maeno, S. Nakatsuji, M. Kosaka, and Y. Uwatoko, Phys. Rev. B **62**, R6089 (2000).
[33] D. Aoki, F. Hardy, A. Miyake, V. Taufour, T. D. Matsuda, and J. Flouquet, Comptes Rendus Physique **12**, 573 (2011).
[34] A. Huxley, I. Sheikin, E. Ressouche, N. Kernavanois, D. Braithwaite, R. Calemczuk, and J. Flouquet, Phys. Rev. B **63**, 144519 (2001).
[35] H. Kotegawa, V. Taufour, D. Aoki, G. Knebel, and J. Flouquet, J. Phys. Soc. Japan **80**, 083703 (2011).
[36] V. Taufour, D. Aoki, G. Knebel, and J. Flouquet, Phys. Rev. Lett. **105**, 217201 (2010).
[37] A. Huxley, S. J. C. Yates, F. Lévy, and I. Sheikin, J. Phys. Soc. Japan **76**, 051011 (2007).
[38] A. Miyake, D. Aoki, and J. Flouquet, J. Phys. Soc. Japan **78**, 063703 (2009).
[39] F. L'evy, L. Sheikin, B. Grenier, and A. D. Huxley, Science **309**, 1343 (2005).
[40] T. Hattori, K. Ishida, Y. Nakai, T. Ohta, K. Deguchi, N. K. Sato, and I. Satoh, Physica C **470**, S561 (2009).
[41] V. A. Sidorov, V. N. Krasnorussky, A. E. Petrova, A. N. Utyuzh, W. M. Yuhasz, T. A. Lograsso, J. D. Thompson, and S. M. Stishov, Phys. Rev. B **83**, 060412 (2011).
[42] D. P. Rojas, J. I. Espeso, J. R. Fernández, J. C. G. Sal, C. Rusu, D. Andreica, R. Dudric, and A. Amato, Phys. Rev. B **84**, 024403 (2011).
[43] P. G. Niklowitz, F. Beckers, G. G. Lonzarich, G. Knebel, B. Salce, J. Thomasson, N. Bernhoeft, D. Braithwaite, and J. Flouquet, Phys. Rev. B **72**, 024424 (2005).
[44] M. J. Steiner, F. Beckers, P. G. Niklowitz, and G. G. Lonzarich, Physica B **329-333**, 1079 (2003).
[45] H. Q. Yuan, M. Nicklas, Z. Hossain, C. Geibel, and F. Steglich, Phys. Rev. B **74**, 212403 (2006).
[46] H. Winkelmann, M. M. Abd-Elmeguid, H. Micklitz, J. P. Sanchez, P. Vulliet, K. Alami-Yadri, and D. Jaccard, Phys. Rev. B **60**, 3324 (1999).
[47] E. D. Bauer, V. S. Zapf, P.-C. Ho, N. P. Butch, E. J. Freeman, C. Sirvent, and M. B. Maple, Phys. Rev. Lett. **94**, 046401 (2005).
[48] N. P. Butch and M. B. Maple, Phys. Rev. Lett. **103**, 076404 (2009).
[49] N. P. Butch and M. B. Maple, J. Phys. Cond. Matt. **22**, 1642204 (2010).
[50] M. Nicklas, M. Brando, G. Knebel, F. Mayr, W. Trinkl, and A. Loidl, Phys. Rev. Lett. **82**, 4268 (1999).
[51] C. Krellner, S. Lausberg, A. Steppke, M. Brando, L. Pedrero, H. Pfau, S. Tencè, H. Rosner, F. Steglich, and C. Geibel, New Journal of Physics **13**, 103014 (2011).